Load Schedule Design Improvements for the Calibration of NASA's Semi–span Balances

N. Ulbrich†
Jacobs Technology Inc., Moffett Field, California 94035

Improvements of the load schedule design for the calibration of NASA's semi–span balances are discussed. These improvements became possible after a minor hardware change was made to Calspan's Large Load Rig. This change moves normal and axial force load points 12 inches closer to the balance moment center. Resulting data quality improvements are significant because Calspan's Large Load Rig cannot currently apply forces at the balance moment center of a semi–span balance. Now, the supported set of rolling and yawing moment arms is 28, 38, and 48 inches. Consequently, the new load schedule design better supports expected normal and axial force locations on semi–span models that are tested in the NASA Ames 11–ft Transonic Wind Tunnel. In addition, estimates of the primary sensitivities of the normal force, axial force, rolling moment, and yawing moment have become more accurate as the applied normal and axial forces have moved closer to the balance moment center. Fundamental moment arm range requirements and Calspan's hardware updates are discussed. In addition, calibration and check load analysis results of NASA's ARC30K semi–span balance are presented to illustrate benefits of the hardware changes.

Nomenclature

AF = axial force of a balance
NF = normal force of a balance
PM = pitching moment of a balance
rAF = electrical output of the axial force gage of a balance
RM = rolling moment of a balance
rNF = electrical output of the normal force gage of a balance
rPM = electrical output of the pitching moment gage of a balance
rRM = electrical output of the rolling moment gage of a balance
rYM = electrical output of the yawing moment gage of a balance
YM = yawing moment of a balance

ΔAF = axial force residuals
ΔNF = normal force residuals
ΔPM = pitching moment residuals
ΔRM = rolling moment residuals
ΔYM = yawing moment residuals

I. Introduction

NASA uses a family of three five–component balances for semi–span model tests at the NASA Ames 11–ft Transonic Wind Tunnel (TWT). These single–piece balances are called MC60, ARC30K, and MC400. They measure the normal force, axial force, rolling moment, yawing moment, and pitching moment on the model. No side force measurement is performed.

The three balances have identical principle dimensions and "balance–to–model" and "balance–to–support" interfaces. The diameter of the metric flange is 15.0 inches. The diameter of the non–metric flange is 27.5 inches. The distance between metric and non–metric balance face is 18.0 inches. Each one of the three balances has a net weight of about 1300 lbs. Therefore, they must be handled with great care. Figure 1 below shows, for example, the overall layout and the principle dimensions of the ARC30K balance.

† Aerodynamicist, Jacobs Technology Inc.

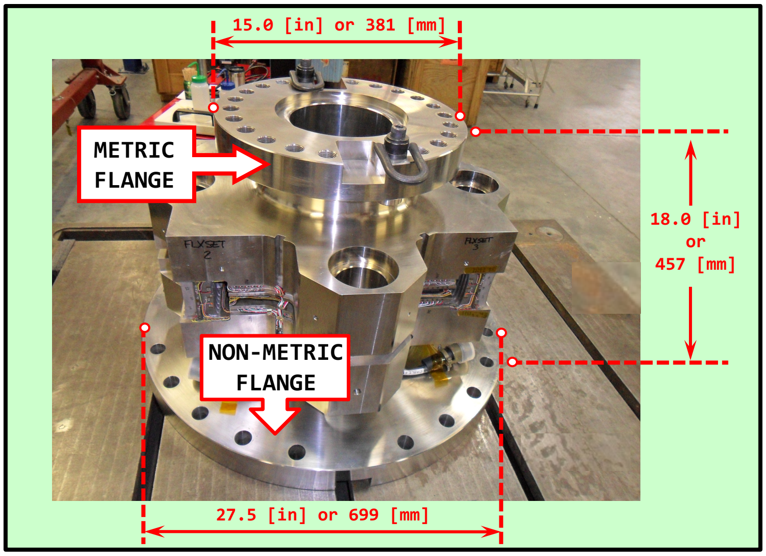

Fig. 1 Layout and principle dimensions of NASA's ARC30K semi–span balance.

The three balances differ in their load capacities. Table 1 below lists capacities of the balances (see also Refs. [1] and [2] for more details). The MC400 balance was originally designed for use in the NASA Ames 12–ft Pressure Wind Tunnel. Therefore, its normal and axial force capacities are significantly larger than the maximum semi–span model loads that are observed in the NASA Ames 11–ft TWT.

Table 1: Capacities of NASA's five–component semi–span balances (side force is not measured).

Balance Name†	*NF, lbs*	*AF, lbs*	*RM, in−lbs*	*YM, in−lbs*	*PM, in−lbs*
MC60 (2019)	6 000	1 200	360 000	72 000	36 000
ARC30K (2021)	30 000	3 000	1 300 000	150 000	300 000
MC400 (2012)	40 000	8 000	2 280 000	480 000	240 000

†Year of most recent calibration in *Calspan's* Large Load Rig (LLR) is listed in brackets.

The balances are mounted on a turntable that is located below the floor of the test section of the NASA Ames 11–ft TWT. This configuration has the advantage that the model weight acts in the direction of the side force. Therefore, its influence on the measurement of aerodynamic loads is minimized as, by design, NASA's five–component balances do not measure the side force. In addition, the natural zeros of the balance gages, i.e., the electrical outputs of the gages in an assumed "weightless" condition can directly be measured whenever the pitch axis of the balance is parallel to the direction of the gravitational acceleration. Figure 2 below shows the ARC30K balance installed in the floor of the test section of the NASA Ames 11–ft TWT.

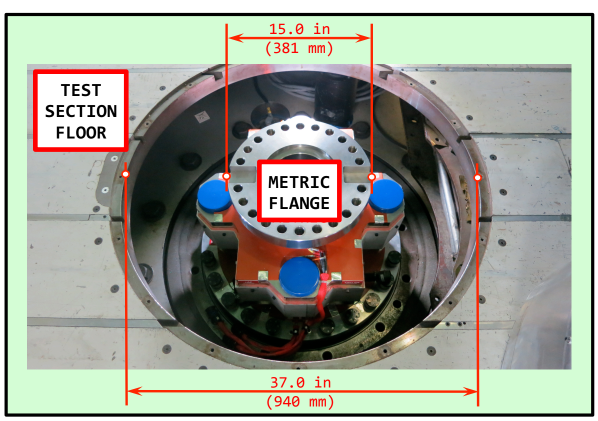

Fig. 2 Installation of the ARC30K balance in the floor of the NASA Ames 11–ft TWT.

In general, the calibration of a high–capacity semi–span balance is challenging because very large loads have to be precisely applied. *Calspan's* Large Load Rig (LLR) is one of the few calibration rigs that NASA can currently use for the characterization of its large semi–span balances.

NASA decided in 2021 to have the ARC30K balance calibrated in support of an upcoming wind tunnel test. Therefore, some improvements of the calibration hardware were implemented that were first proposed in 2012 (see also related discussions in Ref. [3]). These improvements move the load points on the calibration hardware closer to the balance moment center of the balance. Consequently, the expected locations of the normal and axial forces on a typical semi–span model are closer to the center of the moment arm range that the LLR currently supports.

First, relationships between the moment arm range of a calibration rig and the location of the resultant normal and axial forces on a semi–span model are discussed. Afterwards, a modification of the LLR's calibration hardware setup is presented that made it possible to move its load points closer to the balance moment center. Finally, calibration analysis results of the ARC30K balance are discussed in order to illustrate benefits of the calibration hardware improvements.

II. Moment Arm Range Requirement

It is important to review connections between (i) the locations of the resultant normal and axial forces on a typical semi–span model and (ii) the rolling and yawing moment arm range of a calibration rig that is used for the balance calibration. They need to be understood so that calibration data is not used outside its calibration range during a wind tunnel test. It is assumed that the semi–span model of a commercial transport type aircraft is installed on the floor of the test section of the Ames 11–ft TWT. Figure 3 below shows, for example, the installation of the UHB semi–span model in the test section of the tunnel.

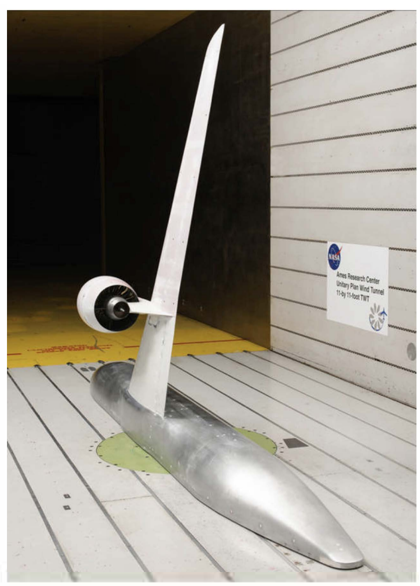

Fig. 3 Installation of the UHB semi–span model in the Ames 11–ft TWT.

First, the connection between normal force and rolling moment arm range is investigated. It is known from theoretical considerations that the resultant "wind–on" normal force on a semi–span model of a commercial transport type aircraft is located somewhere between a point that is close to the metric flange of the balance and a point that is located near 50 % of the semi–span of the model. These two points are shown in Fig. 4 below as a pair of blue points that are located on the pitch axis of the balance. In addition, a typical calibration rig can often only apply the normal force at a small number of selected load points, i.e., rolling moment arms, relative to the balance moment center. The resulting minimum and maximum of the rolling moment arm and the associated "built–in" range of the load points are identified in Fig. 4 below as a pair of green points that are located on the pitch axis of the balance. Consequently, the range of the resultant

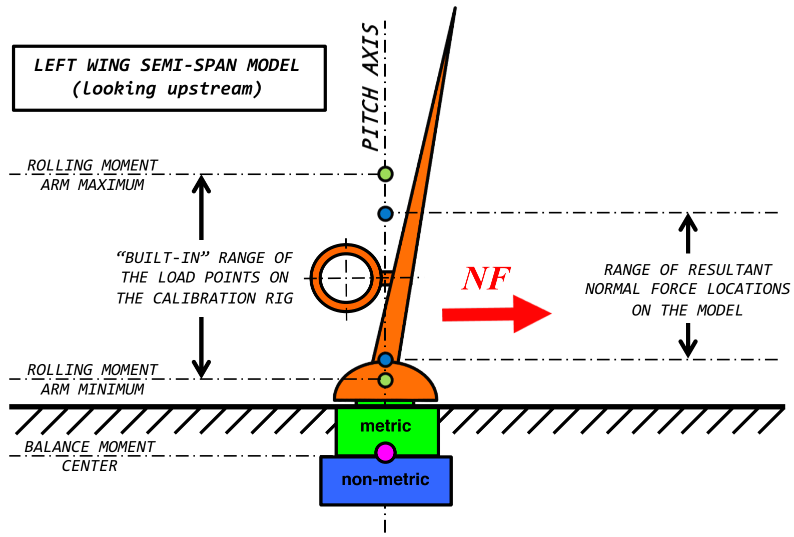

Fig. 4 Rolling moment arm range requirement of the calibration rig.

normal force locations on the model, i.e., the pair of blue points in Fig. 4 above, must be located inside the "built–in" range of the load points on the calibration rig in order to achieve the most accurate normal force predictions. In all other cases, the predicted normal force on the model is extrapolated during the wind tunnel test with an associated reduction of the load prediction accuracy.

Similar relationships between between axial force and yawing moment arm range exist. Figure 5 below shows the corresponding relationships. Again, it is known from theoretical considerations that the resultant

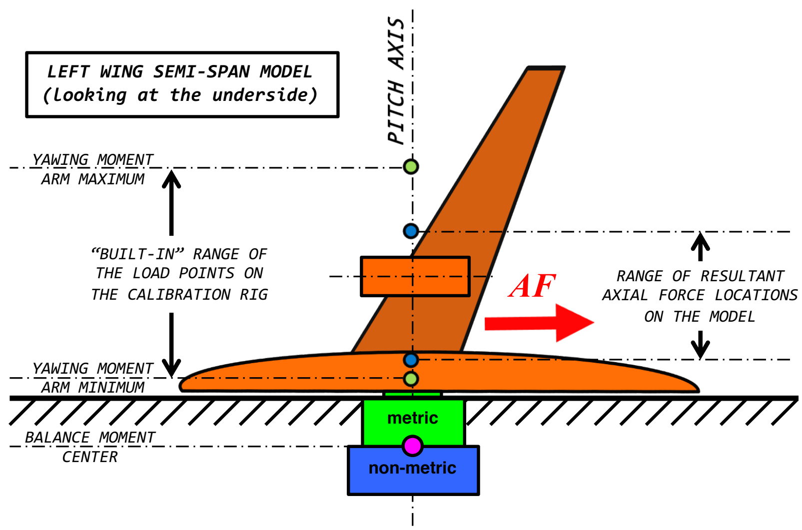

Fig. 5 Yawing moment arm range requirement of the calibration rig.

"wind–on" axial force is located somewhere between a point that is close to the metric flange of the balance and a point that is located near 50 % of the semi–span of the model. These two points are identified in Fig. 5 above as a pair of blue points that are located on the pitch axis of the balance. In addition, a calibration rig can often only apply the axial force at a small number of selected load points, i.e., yawing moment arms, relative to the balance moment center. The resulting minimum and maximum of the yawing moment arm and the associated range of the load points are identified in Fig. 5 above as a pair of green points that are located on the pitch axis of the balance. Again, as it was the case for the normal force, the range of the resultant axial force locations on the model, i.e., the pair of blue points in Fig. 5 above, must be located inside the "built–in" range of the load points on the calibration rig in order to achieve the most accurate

axial force predictions. In all other cases, the axial force will be extrapolated during a wind tunnel test with an associated decrease of the load prediction accuracy.

The discussion of the moment arm range requirements above highlighted the fact that the range of the resultant forces on the wind tunnel model must be within the range of the load points on the calibration rig. *Calspan's* LLR is primarily used to calibrate NASA's semi–span balances that are used at the NASA Ames 11–ft Transonic Wind Tunnel. Physical constraints of the original layout of the LLR limited its minimum rolling or yawing moment arm to 40 inches. Recently, changes were made to LLR's calibration hardware setup so that the load points on its calibration hardware could be moved 12 inches closer to the balance moment center. These modifications are briefly summarized in the next section.

III. Large Load Rig Modification

Figure 6 below shows the general layout and physical constraints of *Calspan's* LLR. The original rolling and yawing moment arm choices of the LLR are 40, 50, and 60 inches. These values were probably chosen to support the calibration of five–component semi–span balances that were used in NASA's 12–ft Pressure Wind Tunnel. In that case, semi–span models were mounted on an image plane that was located 20 inches above the test section floor. No image plane is used for semi–span model testing in the NASA Ames 11–ft Transonic Wind Tunnel. Therefore, the original moment arm range is not an ideal choice for semi–span models that are tested in this facility as the expected locations of the resultant normal and axial forces are near or below the original moment arm minimum of 40 inches. This issue was first identified in 2012.

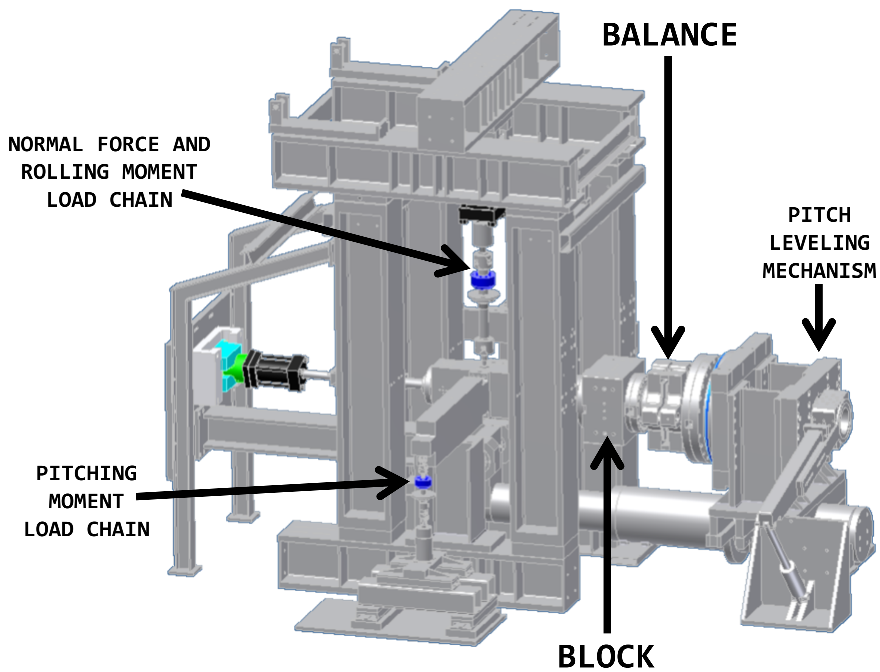

Fig. 6 Physical layout and constraints of *Calspan's* Large Load Rig (LLR) before modification was made (image courtesy of *Calspan Force Measurement Systems*).

Recently, *Calspan* implemented a small change to the LLR's configuration that moved the load points on its calibration hardware 12 inches closer to the balance moment center. The change had the advantage that is could easily be implemented at a modest cost without influencing the normal and axial force load chains that the LLR supports. The change can be described as a simple rearrangement of the existing calibration hardware. Figure 7 below shows the hardware order that was originally used for the application of the normal force and the axial force in the LLR. It consists of three separate parts: (i) load boom, (ii) block, and (iii) balance. *Calspan* suggested to simply install the balance between load boom and block. This change still allows for enough clearance between the LLR's vertical support beams and the pitch leveling mechanism whenever the balance is installed using a 1 ton capacity gantry crane (see also Fig. 6).

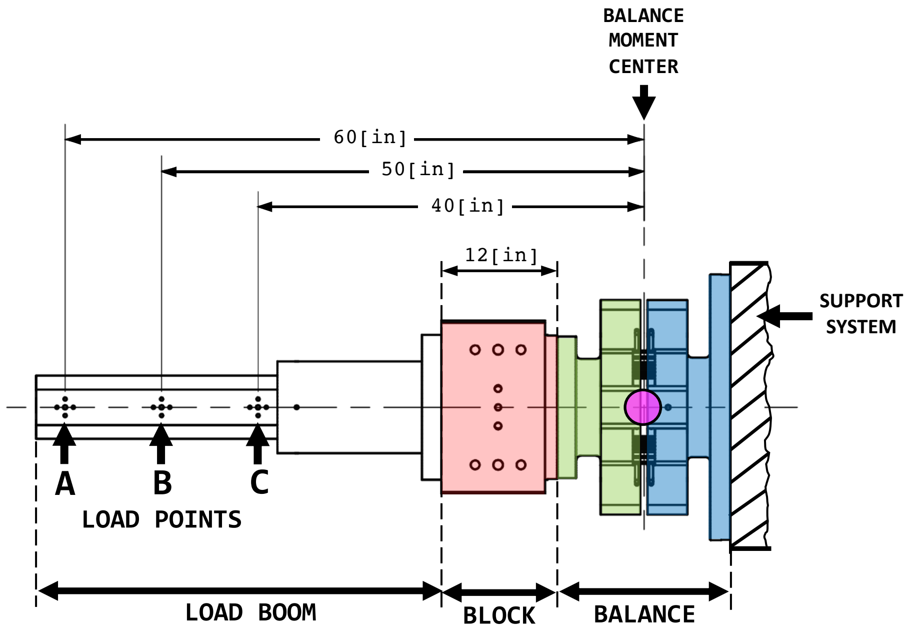

Fig. 7 Detailed view of a semi–span balance with attached calibration hardware before modifications were made (image courtesy of *Calspan Force Measurement Systems*).

Figure 8 below shows the LLR's hardware order before and after the modification was made. The change moved the balance moment center 12 inches closer to the load points as the block has a width of 12 inches. Therefore, the new choices for either the rolling moment or the yawing moment arm are 28, 38, or 48 inches.

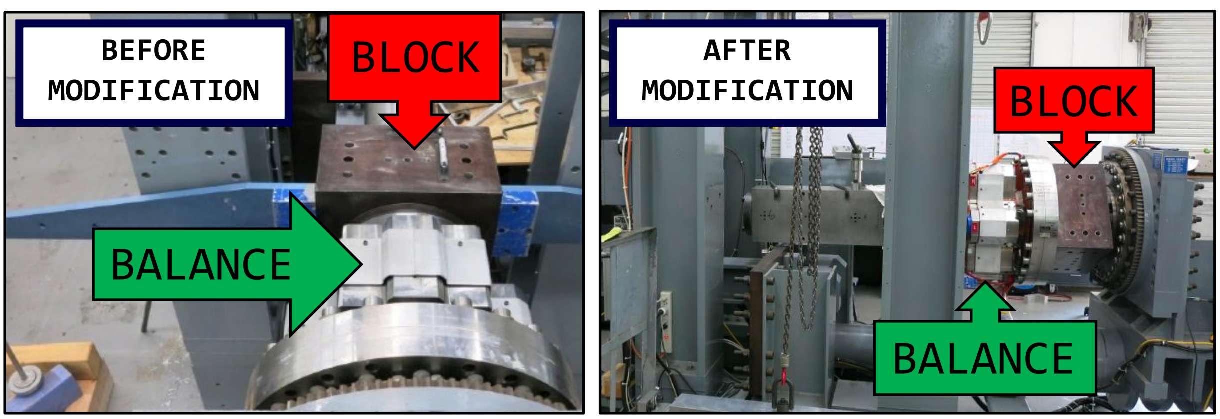

Fig. 8 Balance and calibration hardware arrangement before and after modi–fication was made (image courtesy of *Calspan Force Measurement Systems*).

The 2021 calibration of the ARC30K balance was performed by using the new calibration hardware arrangement. Selected calibration analysis results are discussed in more detail in the next section in order to illustrate benefits of the load schedule design improvements.

IV. Calibration Data Analysis Results

NASA's ARC30K five–component semi–span balance was calibrated in the fall of 2021 by using the LLR's new calibration hardware arrangement. The chosen calibration load schedule consisted of 1015 data points that were distributed across 77 load series. A maximum of five load components were simultaneously applied during the calibration. No single–component loads could be applied because the calibration hardware

configuration did not support those types of loadings. Hydraulic actuators in combination with a load boom were used to apply the normal force, axial force, rolling moment, and yawing moment. Similarly, a hydraulic actuator in combination with a pitching moment arm was used to apply the pitching moment. Electrical outputs of all data points were recorded for both gage sets of the balance. Electrical outputs of "zero load points" were also measured at the beginning of each load series. These outputs are only caused by the weight of the calibration hardware and the metric part of the balance. They are needed so that a tare load iteration for each load series could be performed during the data analysis.

The final analysis of the calibration data of 2021 was performed by using both the *Non–Iterative Method* and the *Iterative Method*. An existing calibration data set of 2013 was also analyzed by using the *Iterative Method* as this data set used the original moment arm set of 40, 50, and 60 inches for the application of the rolling and yawing moments.

The ARC30K balance is a single–piece balance. Its gage outputs are not bi–directional. Therefore, no absolute value terms were needed for the definition of the regression models of the calibration data. Regression model term reduction was performed during the analysis in order to avoid massive linear dependencies between regression model terms that could be caused by "built–in" load application constraints of *Calspan's* LLR. Table 2 below lists primary sensitivities for gage set 1 that were computed during the analysis of the two calibration data sets. A comparison of the sensitivities shows that values for the *Iterative Method* and the *Non–Iterative Method* from the 2021 calibration data show very good agreement. It is also observed that

Table 2: Comparison of primary sensitivities of Gage Set 1 of the ARC30K balance.

Analysis Method (Calib. Date)	*Moment Arm Set*†	$\dfrac{\partial\, rNF}{\partial\, NF}^{\ddagger}$	$\dfrac{\partial\, rAF}{\partial\, AF}^{\ddagger}$	$\dfrac{\partial\, rRM}{\partial\, RM}^{*}$	$\dfrac{\partial\, rYM}{\partial\, YM}^{*}$	$\dfrac{\partial\, rPM}{\partial\, PM}^{*}$
Non–Iterative (2021)	28, 38, 48	$4.0559E{-}2$	$3.9883E{-}1$	$1.0577E{-}3$	$2.0507E{-}3$	$5.4960E{-}3$
Iterative (2021)	28, 38, 48	$4.0603E{-}2$	$3.9812E{-}1$	$1.0588E{-}3$	$2.0502E{-}3$	$5.4981E{-}3$
Iterative (2013)	40, 50, 60	$4.0453E{-}2$	$3.9658E{-}1$	$1.0570E{-}3$	$2.0443E{-}3$	$5.4933E{-}3$

†*inches* ; ‡$(microV/V)\,/\,lbs$; *$(microV/V)\,/\,in{-}lbs$

the sensitivities of the normal force gage and the axial force gage for the new moment arm set are significantly larger than corresponding values for the original moment arm set that was used during the 2013 calibration. The increase of the sensitivities of these two gages is on the order of 0.4 %.

Check load data of the ARC30K balance was recorded in 2022 at NASA Ames Research Center in order to independently verify the accuracy of the load prediction matrices that were generated from *Calspan's* 2021 calibration data set. This check load data can also be used to illustrate the improvement of the load prediction accuracy if the data is processed with the matrices that were obtained from the 2021 and 2013 calibrations. Table 3 below shows standard deviations of the check load residuals that were obtained after processing the check load data with the two matrices from the 2021 calibration and the single matrix from the 2013 calibration. A significant reduction of the standard deviation is observed for the axial force, the rolling moment, and the yawing moment if the check load data is processed with the two matrices from the 2021 calibration (see also values printed in boldface in Table 3 below). These results are expected as (i) the axial

Table 3: Comparison of the standard deviation of the 2022 Ames check load residuals of the ARC30K balance (standard deviations are described as a percentage of the nominal load capacity).

Analysis Method (Calib. Date)	ΔNF	ΔAF	ΔRM	ΔYM	ΔPM
Non–Iterative (2021)	0.0150 %	**0.0267 %**	**0.0064 %**	**0.0435 %**	0.0250 %
Iterative (2021)	0.0156 %	**0.0252 %**	**0.0073 %**	**0.0435 %**	0.0251 %
Iterative (2013)	0.0176 %	**0.1268 %**	**0.0138 %**	**0.0807 %**	0.0241 %

force gage has the highest sensitivity of all balance gages and (ii) the rolling and yawing moments are the two load components of a five–component semi–span balance that are most influenced by a change of the moment arm set. The improvement of the load prediction accuracy of the axial force is remarkable as the standard deviation dropped from 0.1268 % for the 2013 matrix to 0.0252 % for the 2021 matrix. The significance of this drop can be illustrated by plotting the check load residuals of 2022 versus the applied check

load. Figure 9 below shows, for example, the residuals of the check load data if the data is processed with the "iterative" matrix from the 2013 calibration data. An unwanted slope of the residuals is observed. This

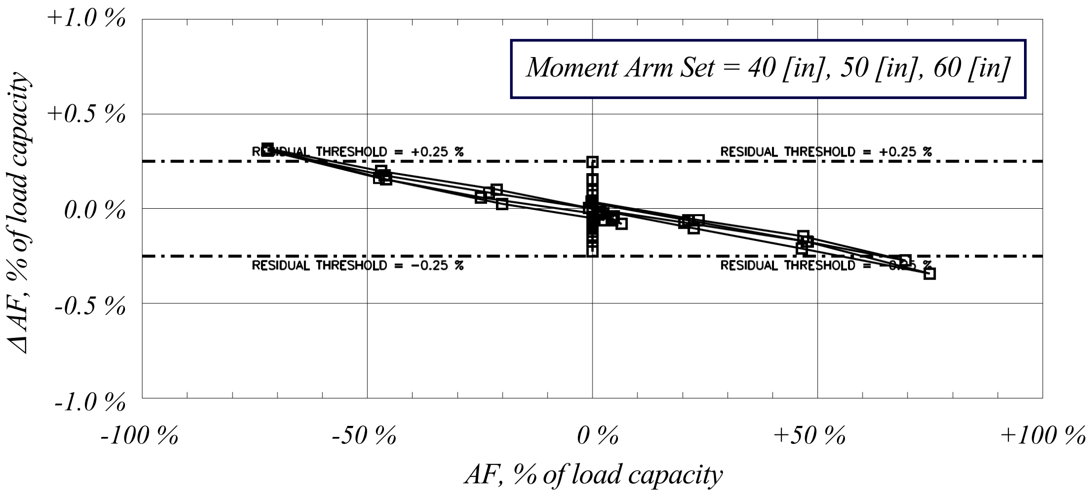

Fig. 9 Check load residuals of the axial force of the ARC30K balance after the check load data of 2022 was processed with the "iterative" matrix of 2013.

slope is caused by a less accurate numerical estimate of the primary sensitivity of the axial force gage that is implicitly contained in the "iterative" matrix of the 2013 calibration data of the balance. Figure 10 below shows the check load residuals if the data is processed with the "iterative" matrix from the 2021 calibration. In this case, no slope is observed in the plot of the check load residuals. The residuals

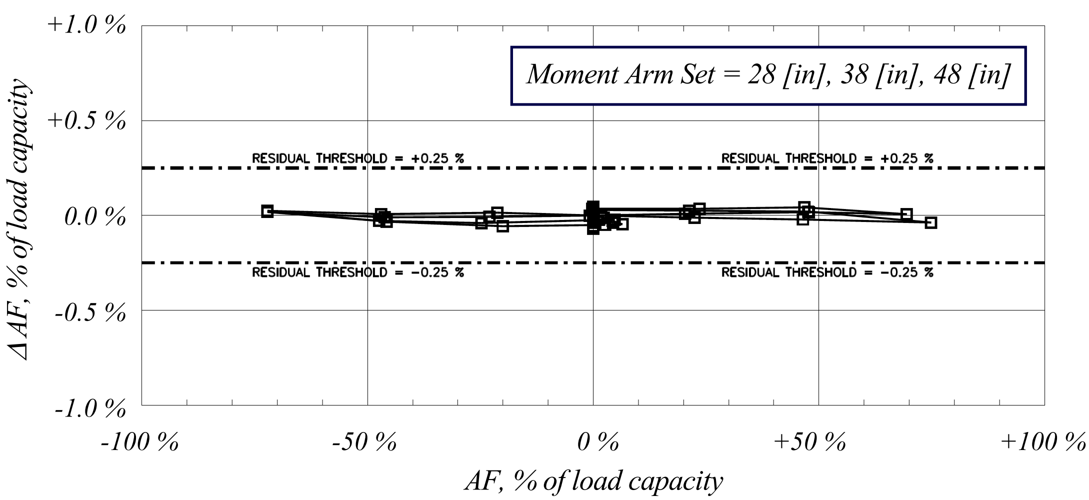

Fig. 10 Check load residuals of the axial force of the ARC30K balance after the check load data of 2022 was processed with the "iterative" matrix of 2021.

are well below the threshold of ±0.25 % of load capacity that is traditionally used in the aerospace testing community for the evaluation of residuals of individual calibration or check load data points.

V. Conclusions and Recommendation

Changes were made to the calibration hardware of *Calspan's* LLR in order to move the LLR's load points closer to the balance moment center of a semi–span balance. The changes resulted in more reliable estimates of the primary sensitivities of the normal force and axial force gages of the balance. Consequently, more accurate predictions of the loads of a five–component semi–span balance have become possible if the balance

is calibrated in *Calspan's* LLR. Independent check load data of NASA's ARC30K semi–span balance was used to illustrate load prediction accuracy improvements that resulted from the modification of the LLR.

In principle, the calibration load schedule of any strain–gage balance should include single–component loads for all load components. Then, the most accurate estimates of the primary gage sensitivities can be obtained as the number of simultaneously applied load components is at its minimum. Unfortunately, the current design of *Calspan's* LLR does not allow for the application of the normal force and the axial force at the balance moment center. However, additional hardware changes of the LLR's configuration are possible that would make the direct use of LLR's normal and axial force load chains at the balance moment center possible. The author recommends to make these changes in the near future. Then, calibration data can be collected in *Calspan's* LLR that will result in very accurate numerical estimates of the primary sensitivities of the normal and axial force gages of a five–component semi–span balance.

Acknowledgements

The author wants to thank Bob Gisler of NASA Ames Research Center for his critical and constructive review of the final manuscript. Support provided by Ryan Kew of *Calspan Force Measurement Systems* is also greatly appreciated. The work reported in this paper was supported by the Wind Tunnel Division at NASA Ames Research Center under contract NNA16BD26C.

References

[1]Ulbrich, N., and Kew, R., "Calibration of the NASA MC60 Five–Component Semi-span Balance," AIAA 2020–3100, paper presented at the AIAA AVIATION 2020 Forum, Virtual Event, June 15–19, 2020.

[2]Ulbrich, N., and Kew, R., "Comparison of two Calibrations of NASA's MC60 Five–component Semi–span Balance," AIAA 2021–0164, paper presented at the AIAA SciTech 2021 Forum, Virtual Event, 11–15 and 19–21 January 2021.

[3]Lynn, K. C., Commo, S. A., Ulbrich, N., Harris, C., "Experimental Design Considerations for Calibration of Semi-Span Force Measurement Systems," AIAA 2014–0276, paper presented at the 52nd AIAA Aerospace Sciences Meeting, National Harbor, Maryland, January 2014.